Holographic Data Storage, Finally…

Kevin Curtis, William L. Wilson, Lisa Dhar, Arturo Hale, and Adrian Hill
Lucent Technologies, Bell Labs

With the invention of new multiplexing and system techniques combined with new types of storage materials, Bell Labs has made significant strides towards establishing the commercial feasibility of holographic data storage. A density of 48.6 bits/μm^2 has been achieved in a photopolymer medium. Materials in hand will result in **5¼** inch disks with 125 GB of user capacity, >40 MB/s read rates, random access, and low cost removable media.

Introduction

Holographic storage has been considered a promising technology for digital data storage since the late 1960's. The inherently three dimensional (3D) aspect of holography makes high-density storage possible because many pages of data can be superimposed in the same volume of material. Additionally, holography has the potential for fast transfer rates and in some cases fast random access times. Fast transfer rates are possible because the data are stored and recovered in parallel - typically 1 million bits at a time. Some storage architectures allow for non-mechanical accessing of the data which can provide sub-millisecond random access times.

The basic concept of holographic storage is illustrated below.

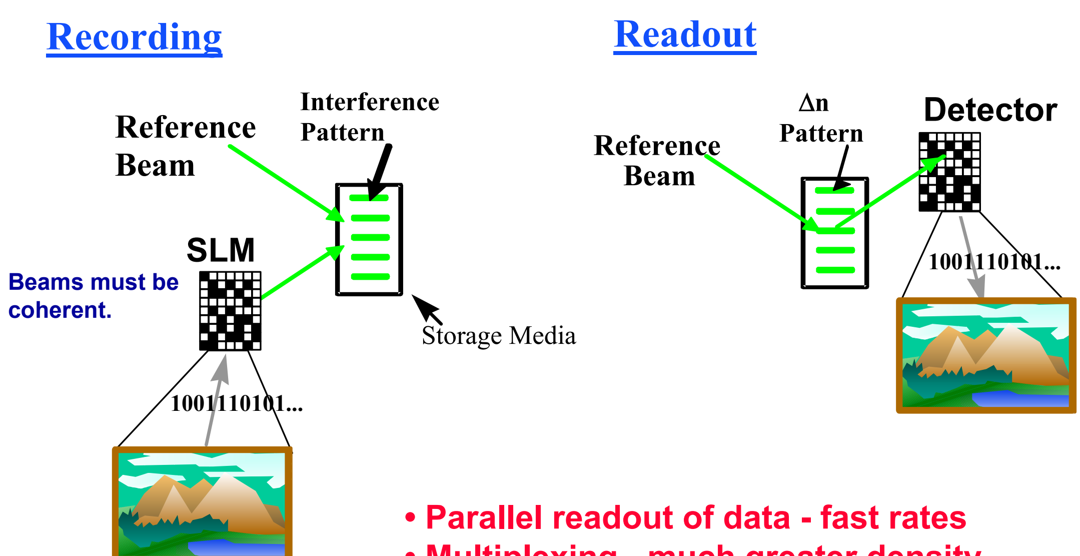

Figure 1. Basic concept of holographic storage.

During recording, the data (a picture in the example shown above) are encoded with error correction and channel codes, and presented to the optical system as pages of binary data using a device called a spatial light modulator (SLM). The SLM consists of approximately 1 million pixels, with each pixel representing a binary 1 or 0 by effectively passing or blocking the light. This modulated beam is then coherently interfered with a reference beam. A coherent laser is required as a source, unlike conventional optical storage (CD's and DVD's) that can use light emitting diodes. The interference pattern of the reference and the modulated beam is then stored as index perturbations (the hologram) throughout the entire volume of the medium.

To achieve high densities, more than one hologram is stored in essentially the same volume by changing some characteristic of the reference beam. This process of superimposing holograms in the *same* volume is called multiplexing. The traditional multiplexing technique is to change the angle of incidence of the reference beam so that each hologram is stored with a unique angle. The separation between holograms relies on the coherent nature of the hologram to reconstruct in phase throughout the volume only if this angle is correct. This phenomenon is called the Bragg effect. Since the required separation between holograms decreases with thickness, more holograms (greater density) can be stored in thicker materials.

To read out the stored data, a reference beam with characteristics matching those used during recording (color, angle of incidence, and position relative to media) illuminates the media and diffracts off the stored index perturbations to reconstruct the stored modulated beam. The bits are then detected in parallel by a multi-element detector such as a CCD camera. Since all 1 million bits are detected (and stored) in parallel the transfer rates can be high - 1Gbit/s. The recovered page is then processed using the channel and error correction codes to reconstruct the original data.

Current Issues

Multiplexing Methods

The traditional multiplexing methods are angle, wavelength, or phase code (a variation of angle). The angle, wavelength (color), or phase of the beams is changed uniquely with each hologram. The amount of change required to adequately separate the holograms is determined by the geometry, wavelength and thickness of the media. Since angle, wavelength, and phase can be changed electronically, sub-millisecond access times are possible. Unfortunately, traditional methods require both extremely complex optical systems and thick (several mm) media achieve commercially relevant capacities.

The existing technology base for spinning disks can be leveraged by the recently invented shift, aperture, and correlation multiplexing techniques. These methods use changes in position of the media relative to the beams for multiplexing. Aperture multiplexing and shift multiplexing use a spherical reference beam.

Correlation multiplexing utilizes a complex reference beam to encode the position of the hologram, as well as leveraging Bragg selectivity in a similar way as shift multiplexing, for extremely high density. At Bell Labs, a storage density of 350 bits/μm^2 (226Gb/in^2) has been experimentally demonstrated in lithium niobate using correlation multiplexing.

Since correlation and shift multiplexing use mechanical motion, their access times will be similar to those typical for optical disks.

Storage Material

The lack of a suitable storage material has plagued the field from its beginning. Most research in holography has been done in photorefractive materials (particularly lithium niobate) which are insensitive, costly, and have limited dynamic range. Recently, a new class of photopolymer material has been developed at Bell Labs that has excellent index contrast, optical quality, and sensitivity. These write-once materials form index changes by light-induced, irreversible polymerization that results in compositional and density fluctuations. High-density write-once read many times (WORM) products can be based on this class of photopolymer.

The invention of correlation and shift multiplexing spurred the development of the storage material. Leveraging Bell Labs' expertise in optical fiber coatings, an extensive research program was undertaken to specify a material, and to characterize the trades-off between system and material parameters. The key challenges to a photopolymer material are: dimensional stability, index contrast, and optical quality. Several research paths were pursued, and several breakthroughs were achieved. First, a method to fabricate optically flat samples using inexpensive substrates was developed. This is critical for the storage of digital data with a high signal to noise ratio. Then, an approach that optimizes the index change relative to the dimensional change was developed. This strategy produced materials with at least 10 times better index change per amount of shrinkage than other polymer media that are being developed elsewhere. Figure 2 shows the progress made in M# (which is proportional to index change and thickness, a good measure of storage material performance) and index change.

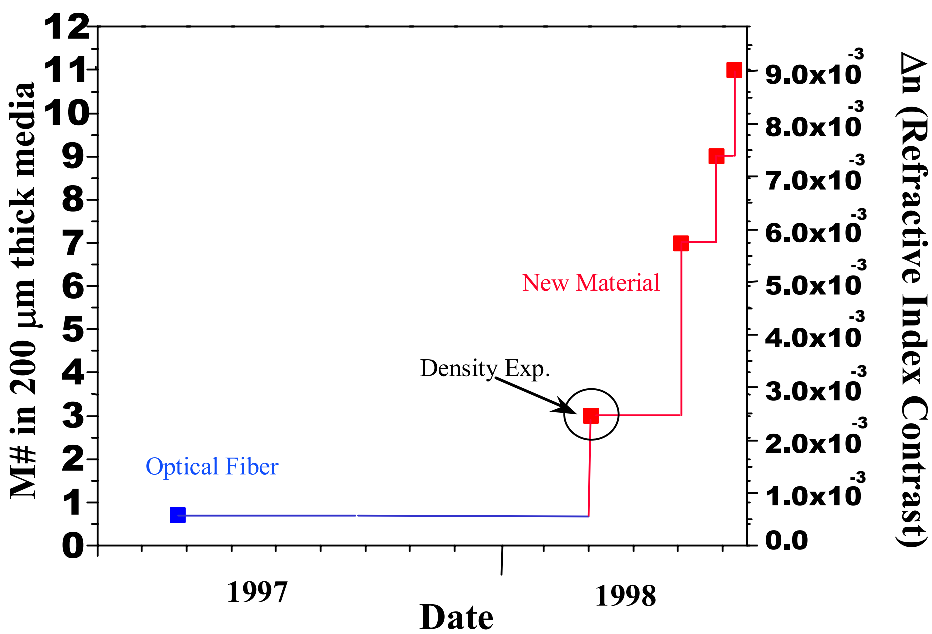

Figure 2. M# which determines readout rate (diffraction efficiency) at a given density vs. time. This is for shrinkage of 0.3% during recording.

A key parameter of any holographic material is its dimensional stability, which is affected by temperature variations and shrinkage incurred during the recording process. Any change in the dimension of the material distorts the reconstructed data and decreases the total energy diffracted off the index perturbations. High-density storage requires large index perturbations (to produce high transfer rates) and small dimensional changes (to ensure high SNR). Figure 3 shows the experimental density achieved in the Bell Labs photopolymer using a combination of shift and aperture multiplexing.

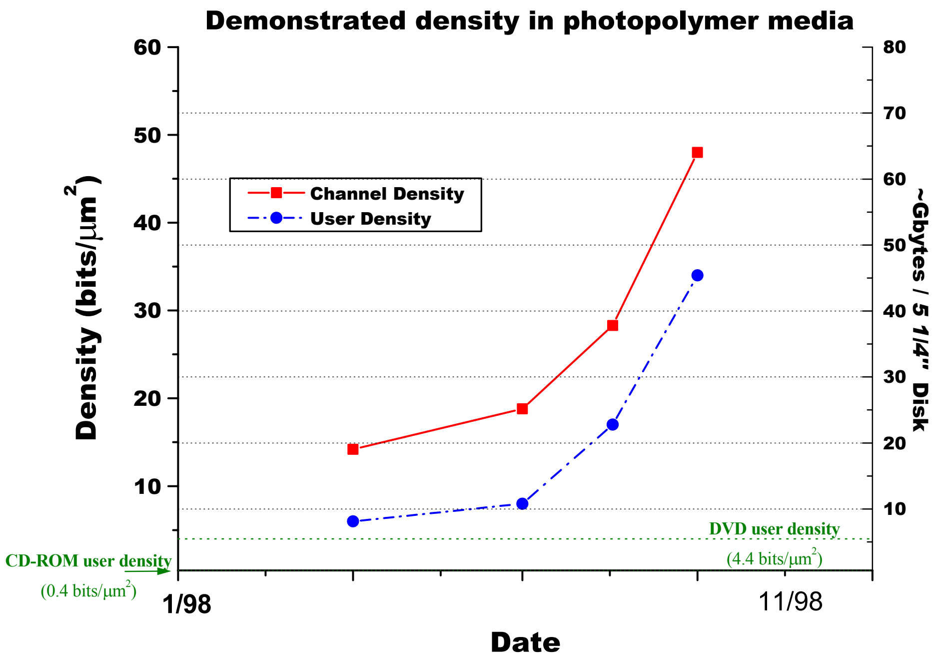

Figure 3. Density in 750 μm thick photopolymer film. This work is the result of a 4 year R&D program.

We have demonstrated a storage density of 48.6 channel bits/um^2 (which scales to a 45 user-GB, 5¼ inch disk) in a digital system that stored approximately 170MB of user data. The density shown above was demonstrated using the basic formulation indicated by the circled point in Figure 2. The dynamic range of this formulation limited the density; however, as Figure 2 shows, improved versions have already been developed. Using these higher response materials will soon result in the demonstration of density sufficient to yield a 125GB disk with read rates greater than 40MB/s.

The Bell Labs' material appears to constitute a commercially viable media with archival lifetime, shelf life, and thermal stability being the critical (non performance) parameters. The shelf life has been investigated, and with sealing to prevent water from entering the media, high quality samples can be maintained. The archival lifetime is being investigated in accelerated aging tests. Currently temperature cycling of up to ~55^{o}C have been carried out, with no discernable effect on signal to noise ratio (SNR).

Components

Until recently, the other system components such as lasers, detectors, and spatial light modulators (SLM) did not exist in any reasonable form. With the invention of solid state laser sources, CMOS active pixel detector arrays, and micro electrical-mechanical (MEM) technology the basic components for a complete holographic storage system now exist.

CMOS detector arrays are simply optical SRAM. These arrays use standard CMOS fabrication and have the access and transfer characteristics of SRAM with low noise at room temperature. MEM-based digital micromirror devices (arrays of 17 μm mirrors) are being sold for display applications. They are excellent SLMs with a large number of pixels, fast (2000 Hz) frame rates, and good optical throughput. Cheap visible lasers, using a microcavity made of gain and doubling crystals only, have been developed for medical, cable TV (optical fiber), and printing markets.

Thus, the basic system components are available commercially. In some cases, the volume of other markets is decreasing the component cost and increasing their reliability. Figure 4 shows a picture of a working research WORM digital storage system using the components mentioned above. The research prototype uses only off-the-shelf optics.

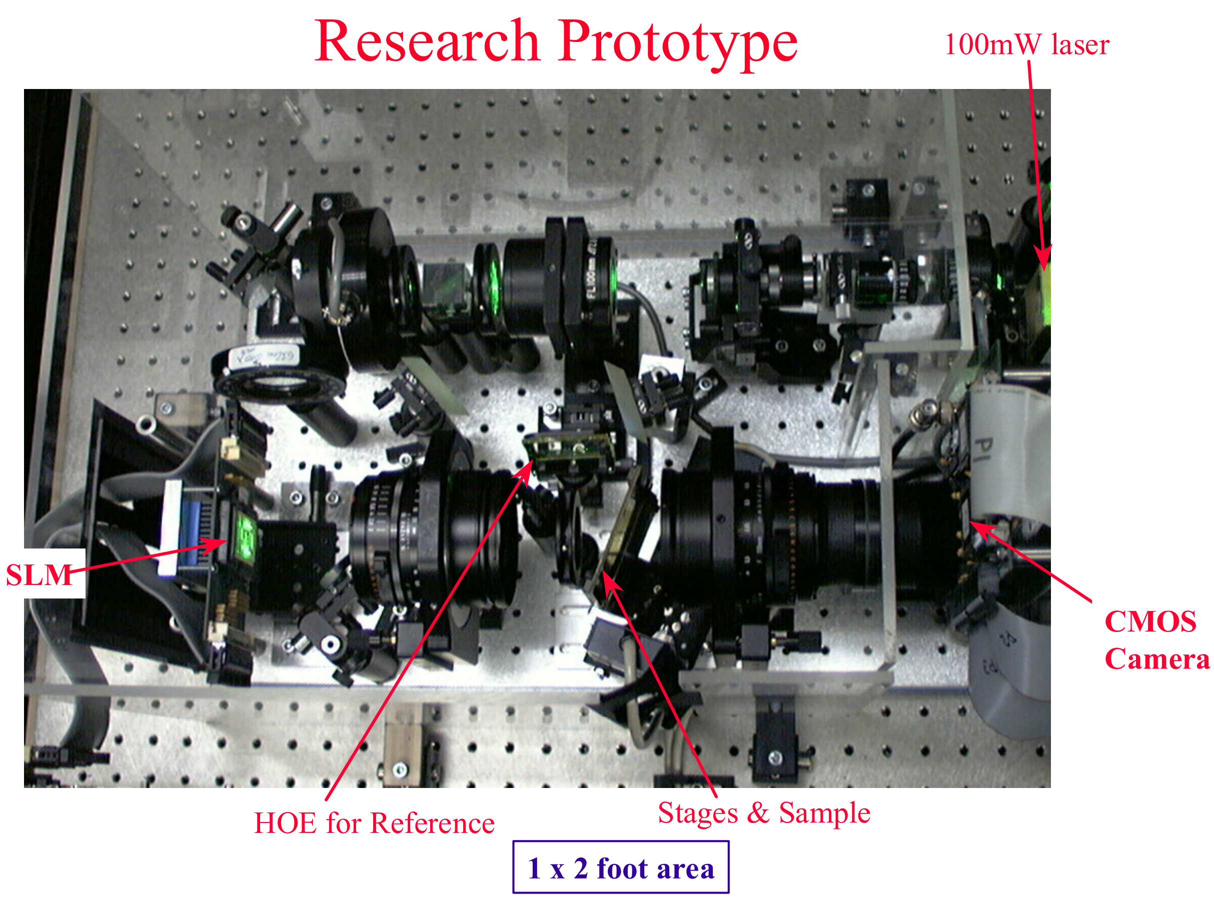

Figure 4: A fully functional WORM prototype system.

Conclusions

Currently, the most promising materials are the inexpensive photopolymers that are necessary write-once, so the nearest term holographic storage product will be a WORM drive. The commercial availability of other system components such as SLM, CMOS detectors, and lasers make holographic storage systems feasible at last. System goals for a first drive are to use removable 5¼ inch media (disk) that will hold 125GB of data, with read rates of 30-50MB/s. The removable media we estimate will cost considerably less than $10 per disk.

The substantial advances described here are the result of a five-year intensive research project in holographic data storage. The commercialization course for technology that falls outside of Lucent's main business has previously involved partnerships and outside investors. Lucent anticipates that holographic storage will soon follow this course.

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Kevin Curtis
Lucent Technologies, Bell Labs
600 Mountain Ave.
Murray Hill NJ 07974
Phone (908) 582-6913
kevincurtis@lucent.com

Dr. Kevin Curtis is a Member of Technical Staff at Bell Laboratories, Murray Hill, New Jersey, and is principal investigator of a group developing holographic storage. He received his BS, MS, and Ph.D. degrees in Electrical Engineering from the California Institute of Technology, Pasadena, California.

Dr. William L. Wilson is a Distinguished Member of Technical Staff at Bell Labs working on holographic systems.

Dr. Lisa Dhar is a Member of Technical Staff at Bell Labs working on holographic materials.

Dr. Adrian Hill is an electrical engineer responsible for the software development and system control.

Dr. Alturo Hale is a Member of Technical Staff at Bell Labs responsible for the synthesis of holographic recording materials.